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EXTREMES OF 1, 12, AND 24 HOUR RAIN FOR MIL-STD-210B.

Robert W. Lenhard, et al

Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

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AIR FORCE SYSTEMS COMMAND
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13. ABSTRACT

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To provide environmental criteria for the design of military equipment is the objective of MIL-STD-210B. The equation was applied to this problem using 0.75 for the precipitation index as typifying the areas of most intense rainfall for calculation of the following average intensities of rainfall in inches per hour that would be exceeded with a probability of 10 percent.

Duration (hours)	Estimated Duration of Exposure (years) 2	5	10	25
1	4.04	4.68	5.16	5.80
12	0.90	1.05	1.17	1.32
24	0.56	0.66	0.74	0.84

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1. INTRODUCTION

"Climatic Extremes for Military Equipment" (MIL-STD-210B), a revision of MIL-STD-210A, will present logical extremes of all meteorological elements that could have an impact on the design of military equipment. Intense rainfall can affect equipment by hampering or preventing operation while the rain is falling. Accumulation of unusual amounts can cause irreversible damage, so that the equipment is worthless for further operation after cessation of the rain. The latter, termed withstanding extremes for design, is of concern in this study.

To withstand rainfall, equipment must be able to survive periods of intense rainfall during expected durations of exposure (EDE) in the field. The length of the periods of intense rainfall that could be critical and the EDE will vary with the equipment. Hence rainfall intensity data must be provided for various periods of precipitation and EDEs. Military Standard 210B specifies duration of 1, 12, and 24 hours and EDEs shall be 2, 5, 10, or 25 years, as considered appropriate for each item of equipment. For these periods, a calculated risk of failure of 10 percent in the most severe geographical area for each climatic element is acceptable for "withstanding." Data on extreme annual precipitation are available in the form of return periods. The approximate return periods that will give a 10 percent chance of occurrence within the specified planned life spans are:

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EDE (years)	2	5	10	25
Return period (years)	20	50	100	250

2. DATA

To determine values of rainfall for various durations, that is, 1, 12, and 24 hours for specific return period, extreme probability theory (Gumbel, 1958; Gringorten, 1963) is used. Tabulation of annual extremes for these durations for many years are required. Although there are many stations throughout the world where precipitation is measured, there are relatively few where amounts are tabulated and published for time periods of less than 24 hours. In tropical regions, where the most intense precipitation is to be expected and therefore of greatest military interest, published data on annual extremes of rainfall are even less available than for the highly industrialized mid-latitudes. In order to provide climatological information on a world-wide basis, it is necessary to relate data available on extreme rainfall for mid-latitudes to the usual meteorological observations for which a world-wide climatology is available.

Rainfall data suitable for establishing such a relationship are published in USWB Technical Paper No. 25 (1955) which presents data for 200 stations in the contiguous United States plus 1 station each in Alaska, Hawaii, and Puerto Rico. Data are presented as rainfall intensity-duration curves for return periods of 2, 5, 10, 25, 50, and 100 years by station. Duration ranges from 5 minutes to 24 hours. The curves are based on the maximum rainfall for each year for each duration. Curves for the return periods are spaced according to the Fisher-Tippet type I (Gumbel) distribution. As an example of the form of data presentation, the set of curves for Pensacola, Florida is reproduced in Figure 1. This is the station with the most intense rainfall of the 203 available. Rainfall amounts were extracted for all of the stations for a range of durations and return periods. The durations and periods used in the analysis are shown in Table 1, which also contains the average rainfall rates for Pensacola as extracted from Figure 1.

Similar intensity-duration curves are available for only a limited number of locations outside of the United States, a few in areas of high rainfall. Included in this study are: Hong Kong (Cheng and Kwok, 1966); Bombay (Patel and Vanjari, 1969); Nagasaki and Yokohama, Japan; Naha, Okinawa; Manila, San Fernando and Olangapo, P.I. (Paulhus, 1964).

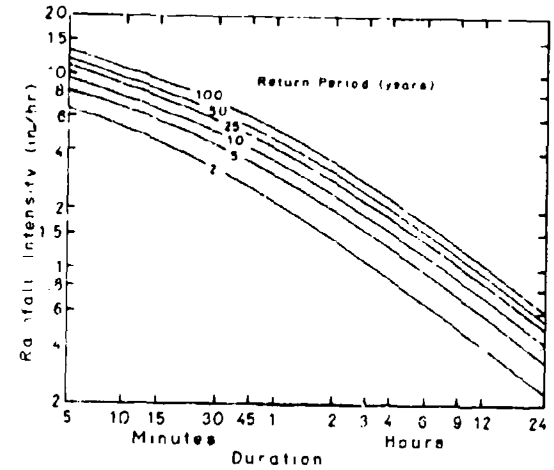

Figure 1. Rainfall Intensity-Duration-Frequency Curves for Pensacola, Florida

Table 1. Rainfall Rates (in./hour) Exceeded at Pensacola, Florida

Duration	Return period (years)			
	2	10	50	100
5 min	6.6	9.4	11.9	13.0
15 min	4.5	6.5	8.1	9.2
30 min	3.2	4.9	6.3	7.0
1 hr	2.2	3.6	4.6	5.1
3 hr	1.1	1.9	2.5	2.8
6 hr	0.68	1.2	1.6	1.7
12 hr	0.40	0.70	0.96	1.1
24 hr	0.23	0.41	0.55	0.61

3. ANALYSIS

The objective of the analysis is to relate extremes of 1, 12, and 24 hour rainfalls to climatological data that are widely available. The simplest hypothesis is that the greatest extremes will occur in areas of greatest total precipitation. Indeed there is a correlation between annual precipitation total and the intensity of extreme rainfall that is statistically significant. The relationship is of limited practical value, however, as the correlation is not high, and the standard error of estimate of the regression equation is fairly large. A more sophisticated hypothesis is one that would take account of the distribution of the average daily intensity of rainfall. This may be achieved by using the average precipitation on a rainy day, obtained by dividing the annual precipitation by the number of days on which precipitation occurred. This parameter has been designated as the precipitation index (I) and the primary independent variable in the relationships that have been developed. It is fairly high in correlation with extreme intensities, and the relationship has a standard error that, although larger than desirable, is small enough to have practical value for estimated intensities.

Other predictors were tried, alone and in multiple regressions. Only those involving the frequency of thunderstorms and temperature yielded any significant results. Several variables were created to serve as indices of thunderstorm activity, for example, number of days with thunderstorms/number of days with rain. Some variables improved the intensity estimates considerably and were statistically significant. However, these were abandoned with great reluctance owing to an anticipated lack of availability of thunderstorm climatology and uniformity of observations. It was believed that there would be areas in which stations providing thunderstorm climatology would be scarce and that where data were available, there would be differences between regions in the climatology presented. Specifically, the count of number of days with thunderstorms was suspect. The authors believed it quite likely that this statistic would not have the same meaning in all regions of the world.

The temperature parameter found by trial to be most useful was an average measure of the annual temperature range: the difference in mean monthly temperature in Fahrenheit degrees between the warmest and coldest months. This parameter (dT) was taken as the secondary independent variable.

Regression equations were established for each return period and duration based on data from all stations. A few of these equations were checked against several of the stations with most intense precipitation. There seemed to be some slight tendency to underestimate these extreme values. Hence it was decided to select a smaller sample of stations with high rates of precipitation. In the United States, these stations were located near the coast, from South Carolina

southward on the Atlantic coast and all along the Gulf coast from Brownsville, Texas to Key West, Florida. All previously listed stations outside of the United States were included in this smaller sample, consisting of 27 stations.

Regression equations were established based on this sample. The correlations were lower than for the regressions based on all stations but so was the standard error of estimate. For this small sample, multiple regression was of no value; the contribution to explained variance of the variable dT was not statistically significant, nor was the standard error of estimate improved appreciably. Regressions utilizing all stations were improved by the addition of dT as an independent variable in all but the 12 and 24 hour durations. The standard error of rates estimated from these regressions was, however, larger than for estimates made from regressions on (I) only, derived from the sample of 27 stations. Since these 27 stations have the most intense precipitation and provide the greater precision of estimate, the model to be developed will be based on them.

The estimating equation to be used is

$$R = A + BI , \tag{1}$$

where R is the rain rate in inches per hour and I is the precipitation index in inches per day of rainfall ≥ 0.01 inch. Since there are 8 durations (D) and 4 return periods (P), the equation can be rewritten with subscripts to denote the particular duration and return period:

$$R_{DP} = A_{DP} + B_{DP} I . \tag{1a}$$

The 32 regression equations were determined by least squares and the coefficients are shown in Figures 2 and 3 on a semilogarithmic scale. They appear to increase linearly with the logarithm of P, the return period. This relationship is expressed by

$$C_{i_D} = a_{i_D} + b_{i_D} \ln P , \tag{2}$$

where C_i is the coefficient, either A or B; for example, $A_5 = a_{A5} + b_{A5} \ln P$.

This model was fitted by least squares to the 16 sets of values (2 coefficients $\times$ 8 durations) with all fits being highly significant statistically. The lowest correlation obtained was 0.967 which provided an F ratio that was significant at the 3 percent level. The values of the coefficients a_{i_D} and b_{i_D} are shown in Figure 4 on a log-log scale. There appears to be a quadratic relationship between the value of a coefficient and D, the duration. This relationship is expressed by

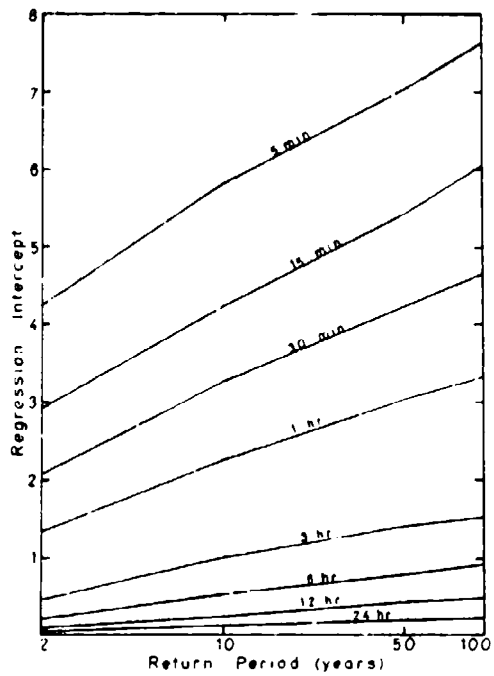

Figure 2. Intercept of Regression Lines Fitted to 27 Rain Rates for Durations Specified

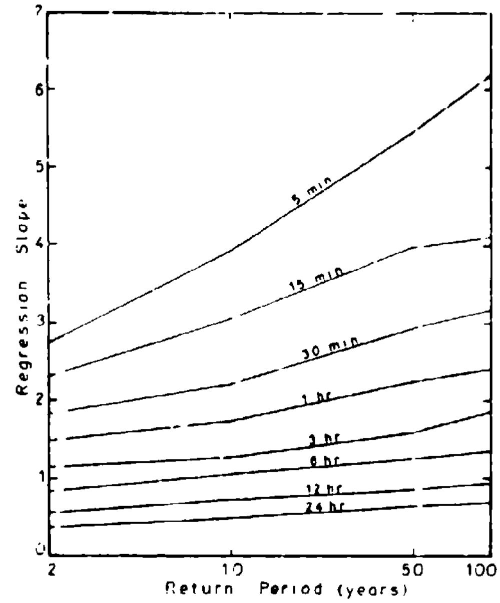

Figure 3. Slope of Regression Lines Fitted to 27 Rain Rates for Durations Specified

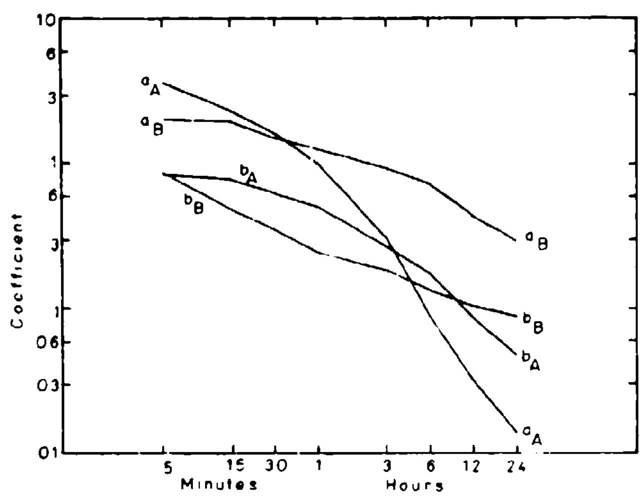

Figure 4. Coefficients of $C_i = a_i + b_i \ln P$

$$\ln K_j = \alpha_j + \beta_j \ln D + \gamma_j \ln^2 D \,, \tag{3}$$

where K_j is the coefficient a_{iD} or b_{iD} in Eq. (2), for example, $\ln a_{AD} = \alpha_A + \beta_A \ln D + \gamma_A \ln^2 D$.

This model was fitted to the 4 sets of coefficients yielding the following four equations, all with correlations greater than 0.99.

$$\ln A_a = 1.3312 + 0.22135 \ln D - 0.13889 \ln^2 D \tag{4a}$$

$$\ln A_b = -0.46243 + 0.33652 \ln D - 0.09462 \ln^2 D \tag{4b}$$

$$\ln B_a = 0.58770 + 0.15912 \ln D - 0.05524 \ln^2 D \tag{4c}$$

$$\ln B_b = 0.81299 - 0.62919 \ln D + 0.02514 \ln^2 D \tag{4d}$$

Equations (1) and (2) can be combined into a general equation,

$$R_c = (A_a + A_b \ln P) + (B_a + B_b \ln P)\, I \,, \tag{5}$$

and the values of the coefficients A_a, A_b, B_a and B_b determined from Eqs. (4). Here R_c is used to designate the computed or estimated value of precipitation as distinguished from R, the observed value that was the input to the analysis.

4. EVALUATION

4.1 Effect of Smoothing Regression Coefficients

Ordinarily with least-squares regression, it is possible to make a statement of the precision of the estimate yielded by the equation by presenting the standard error of estimate. This can be done for the initial stage of 32 equations (1). When equations (2) are determined, the standard error obtained applies to the estimated values of coefficients in equations (1), not to the values of R estimated from those equations.

In turn, the use of Eq. (3) to obtain estimates of coefficients in Eq. (2) does not give a measure of the precision of estimate for rainfall.

The only way to obtain a statement of the precision of estimating R from the smoothed regression coefficients is by calculating the actual individual differences, $R - R_c$, between observed and estimated values for each station, duration, and return period. These differences can be accumulated and compared to the standard error

obtained from the basic regressions (Eq. 1). For purposes of this comparison, the statistic to accumulate would be the root-mean-square

$$\mathrm{RMS} = \left[(R - R_c)^2 / N \right]^{1/2} .$$

In error theory this is a statement of precision, a statement of variation about a zero mean with positive and negative deviations being equal in number and magnitude. The standard error of estimate in regression is an analogous statement of variation about the regression curve, with positive and negative deviations being equal in number and magnitude. In this case, however, the deviations are about a curve that is no longer the least-squares regression so that positive and negative deviations are no longer equal. In fact, there can be a net bias and the mean of the deviations can be other than zero. One could compensate for this by calculating the standard deviation σ, a measure of the dispersion of the deviations about their mean. However, this is not a measure of the precision of the estimate.

In order to accomplish an evaluation, both the RMS and σ values were calculated, along with the mean deviation for each of the 32 combinations of duration and return period. These are presented along with the standard error of estimate from the basic regressions (Eq. 1) in Table 2. Fortunately, the mean deviations

Table 2. Measures of Precision of Estimate*

D \ F	Standard Error (in./hr)				RMS (in./hr)			
	2 (years)	10 (years)	50 (years)	100 (years)	2 (years)	10 (years)	50 (years)	100 (years)
5 min	0.5337	0.7515	1.1711	1.3170	0.5390	0.7532	1.1720	1.3176
15 min	0.3999	0.5467	0.7655	0.7741	0.4052	0.5470	0.7671	0.7771
30 min	0.2737	0.4415	0.5785	0.5794	0.2771	0.4443	0.5793	0.5839
1 hr	0.1653	0.3032	0.4144	0.4385	0.1661	0.3113	0.4150	0.4404
3 hr	0.1359	0.1857	0.2680	0.3188	0.1378	0.1945	0.2706	0.3219
6 hr	0.1018	0.1458	0.2005	0.2268	0.1026	0.1528	0.2042	0.2304
12 hr	0.0739	0.1072	0.1567	0.1810	0.0740	0.1079	0.1568	0.1810
24 hr	0.0493	0.0734	0.1070	0.1194	0.0505	0.0736	0.1078	0.1202
	σ (in./hr)				Mean (in./hr)			
5 min	0.5340	0.7517	1.1711	1.3173	-0.0732	0.0475	-0.0459	0.0278
15 min	0.4004	0.5469	0.7664	0.7741	-0.0625	-0.0088	-0.0332	-0.0679
30 min	0.2739	0.4432	0.5786	0.5796	-0.0420	0.0312	-0.0279	-0.0704
1 hr	0.1656	0.3055	0.4149	0.4394	0.0133	0.0601	-0.0097	-0.0291
3 hr	0.1367	0.1858	0.2680	0.3204	0.0175	0.0574	0.0374	0.0305
6 hr	0.1024	0.1466	0.2008	0.2270	0.0075	0.0431	0.0375	0.0389
12 hr	0.0739	0.1073	0.1568	0.1810	-0.0047	0.0120	-0.0012	0.0012
24 hr	0.0493	0.0735	0.1071	0.1195	-0.0108	-0.0016	-0.0129	-0.0135

* Standard Error of basic regressions [Eq. (1)]; other measures calculated from deviations ($R - R_c$) between actual values and estimates from equations with smoothed coefficients for 27 station subset.

from the equations with smoothed coefficients are small so that there is little difference between the values of σ and RMS. In fact, the RMS is only slightly larger than the standard error of estimate of the basic regressions. Hence it is concluded that the calculation of precipitation rates based on Eqs. (4) and (5) is a valid procedure.

4.2 Effect of Limiting Sample Size

If the complete set of 211 stations is used to determine the regression equations, the variable dT contributes significantly to the explained variance. The subset of 27 stations indicated that dT did not contribute significantly. Thus there are two plausible approaches to using the information from the full data set in estimating extreme precipitation rates: A simple relationship to precipitation index (I) or a multiple relationship to both I and dT. Both sets of equations were used and the deviations ($R-R_c$) between the observed and computed values for the 27 stations subset were compiled into RMS statistics which are presented in Table 3. Nearly all of the values in Table 3 are appreciably larger than the RMS values based on equations derived from the subset as shown in Table 2. Hence it is concluded that limiting the analysis to the 27 stations with extreme precipitation rates is profitable.

Table 3. RMS Deviation ($R-R_c$) Between Actual and Estimated Values for 27 Station Subset Based on Equations With Smoothed Coefficients Derived From All Sations

P / D	I only				I and dT			
	2	10	50	100	2	10	50	100
5 min	1.3227	1.1266	1.3608	1.5016	1.2770	1.5691	1.9147	2.0834
15 min	0.8563	0.9679	1.1051	1.1458	1.0474	1.3991	1.7540	1.8541
30 min	0.6340	0.8330	0.9471	0.9779	0.7860	1.1675	1.4383	1.5231
1 hr	0.4232	0.6541	0.7909	0.8552	0.5432	0.8593	1.0753	1.1706
3 hr	0.2024	0.3822	0.5293	0.5862	0.2410	0.4426	0.6082	0.6712
6 hr	0.1292	0.2484	0.3583	0.4084	0.1354	0.2703	0.3951	0.4520
12 hr	0.0893	0.1632	0.2346	0.2702	0.0824	0.1600	0.2401	0.2794
24 hr	0.0643	0.1166	0.1608	0.1813	0.0599	0.0921	0.1227	0.1363

5. APPLICATION

5.1 Precision of Estimate

Whatever the application, a knowledge of the precision of the estimate may be desired. This may be obtained from the RMS section of Table 2. The usual interpretation of the RMS statistic is based on the assumption of a normal frequency distribution with zero mean. The frequency distributions of the deviations $(R-R_c)$ were checked for skewness and kurtosis. A few of the 32 sets were nearly normal but most departed from normal but not by great amounts. There was no pattern for the departures. It is probable that no great error would be made in accepting the usual interpretation of the statistic; that is, that the true value of R lies in the range $R_c \pm$ RMS with a probability of 63 percent.

When the regression equations are extended beyond the range of the data, either in duration or return period, Table 2 will not provide an estimate of the RMS deviation. The values listed in Table 2 show an orderly progression as did the coefficients in the regression equations. The RMS values are linearly related to the logarithms of the return period as can be seen in Figure 5. The relationship is expressed by

$$\text{RMS} = A + B \ln P \tag{6}$$

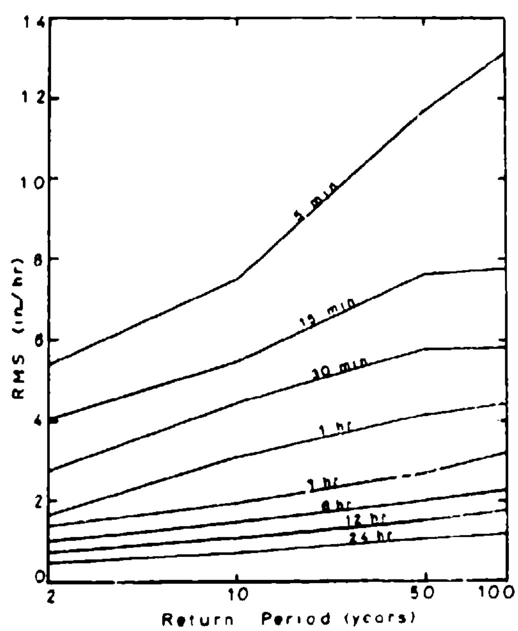

Figure 5. RMS Deviation $(R-R_c)$ Between Actual and Computed Precipitation Rates for Sample of 27 Stations

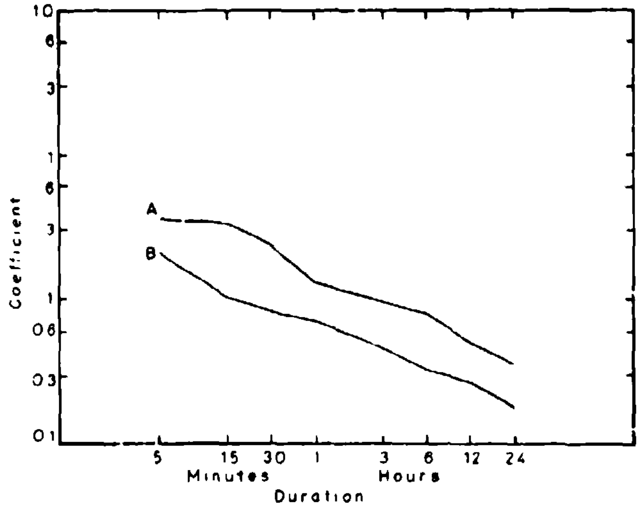

Figure 6. Coefficients of RMS = A + B ln P

which was fitted by least squares and the behavior of the coefficients A and B examined. A linear relation appears in Figure 6 where A and B are plotted against duration on a log-log scale. Least-squares regression yielded the following expressions for A and B in Eq. 6:

$$\ln A = -0.14536 - 0.42516 \ln D \tag{7a}$$

$$\ln B = -1.06942 - 0.39679 \ln D \tag{7b}$$

5.2 Military Standard 210B

To obtain values of R for MIL-STD-210B using Eqs. 4 and 5, a value must be assigned to the precipitation index (I). This should be representative of the most severe geographical area. The areas with most intense rainfall are found in Africa on the Gold Coast, in South America in Columbia and in the Philippines, Indonesia, South East Asia and India. The annual precipitation index was calculated for a number of stations in the Asian region which has the largest area of intense rainfall. A few stations have an index greater than 1 inch per rain day of 0.01 inch or more, but these are relatively rare and isolated. Most of Southeast Asia, India, Indonesia and the Philippines have an index greater than 0.5 in. per day. A number of stations in Burma and Southeast Asia yielded index values above 0.75 in. per day and formed coherent regional patterns. This index value appeared to be representative of areas of greatest rainfall intensity

without being of such unusual occurrence as to produce an unrealistically stringent design criterion that would cause excessive overdesign of equipment. Hence I = 0.75 was selected for input into Eqs. 4 and 5 for calculating values of intense rainfall for MIL-STD-210B.

For the purposes of MIL-STD-210B the durations of interest are 1, 12 and 24 hours and the return periods, as stated previously are 20, 50, 100 and 250 years. The coefficients obtained from Eqs. 4 and 2 are given in Table 4.

Table 4. Coefficients for Calculating Rain Rates for MIL-STD-210B

Coefficient	Duration (hours)		
	1	12	24
A(a)	0.9132	0.0398	0.0122
A(b)	0.5113	0.0959	0.0488
B(a)	1.3678	0.4693	0.3083
B(b)	0.2514	0.0966	0.0778
20 yr A	2.4450	0.3272	0.1585
B	2.1209	0.7588	0.5413
50 yr A	2.9135	0.4151	0.2033
B	2.3512	0.8473	0.6125
100 yr A	3.2679	0.4815	0.2371
B	2.5255	0.9143	0.6664
250 yr A	3.7364	0.5694	0.2819
B	2.7559	1.0028	0.7377

5.3 Definition of Precipitation Index

The precipitation index (I) has been defined as the total annual precipitation in inches divided by the number of days with 0.01 inch of precipitation. This was chosen because the climatological records for almost all of the stations used in this study contained the parameters in these units. There is no problem in converting total annual rainfall from millimeters to inches. Unfortunately, not all nations define a day with precipitation in the same manner. Some count days with 1 mm or 0.1 mm or 1/10th inch. When these are encountered it is necessary to convert to the number of days with 0.01 inch in order to calculate the index for use in Eq. (5). Conrad and Pollak (1950) present a technique for doing this by calculating the probabilities p_0, p_1, p_2, ..., p_i of days with 0, 1, 2, ... i units of rainfall. This is described by

$$p_i = p_{i-1} \frac{h + (i-1)\,d}{i\,(1+d)}$$

and

$$p_0 = \frac{1}{(1+d)^{h/d}} ,$$

where h = RR/N, RR is the total rainfall for the period in the units specified and N is the total number of days involved. This would be 365.25 when dealing with a yearly average record. Thus h is a fictitious average rainfall for one day. The variable d represents the degree of dependence of one rainfall event on another. It must be determined from the record which will give the count n_i of the number of days with rainfall equal to or greater than i units. Then $(N-n_i)/N$ is the probability of less than i units of rain occurring. This probability is also given by $\sum_{o}^{i} p_i$. Trial values of d are assumed, Σp_i is calculated and compared to $(N-n_i)/N$ until a value of d is found that equates the two estimates. Note that the units involved are not millimeters or inches. When converting from days with 0.1 in. or more of rainfall, one finds that the unit is 0.01 in., i = 10 and an annual total of 23.41 inches is 2341.

6. SUMMARY

6.1 Method

A method of estimating extreme rainfall amounts likely to occur during a specified time interval D with a return period P from widely available climatological data has been developed. The climatological input is the precipitation index (I) obtained by dividing the total annual rainfall in inches by the number of days with 0.01 inch or more of rain. The method is described by the following equations where R is the estimated rainfall:

$$R_c = A + B\ I$$

$$A = A_a + A_b \ln P$$

$$B = B_a + B_b \ln P$$

$$\ln A_a = 1.33123 + 0.22135 \ln D - 0.13889 \ln^2 D$$

$$\ln A_b = -0.46243 + 0.33652 \ln D - 0.09462 \ln^2 D$$

$$\ln B_a = 0.58770 + 0.15912 \ln D - 0.05524 \ln^2 D$$

$$\ln B_b = 0.81299 - 0.62919 \ln D + 0.02534 \ln^2 D$$

The standard error of estimate (RMS) of R from the foregoing equations may be approximated by

$$RMS = \alpha + \beta \ln P$$

where

$$\ln \alpha = -0.14536 - 0.42516 \ln D$$

$$\ln \beta = -1.06942 - 0.39679 \ln D$$

The model is restricted in applicability to areas of intense rainfall such as the tropics.

6.2 Application

For MIL-STD-210B a precipitation index value of 0.75 was used to calculate the following average intensities of rainfall in inches per hour that would be exceeded with a probability of 10 percent:

Duration (hours)	Estimated Duration of Exposure (years)			
	2	5	10	25
1	4.04	4.68	5.16	5.80
12	0.90	1.05	1.17	1.32
24	0.56	0.66	0.74	0.84

References

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Appendix

List of Stations in Sample

Station	Index	Station	Index
Apalachicola, Fla.	0.530	Nagasaki, Japan	0.463
Austin, Tex.	0.402	Naha, Okinawa	0.499
Bombay, India	0.711	New Orleans, La.	0.534
Brownsville, Tex.	0.377	Olangapo, P.I.	1.222
Charleston, S.C.	0.427	Pensacola, Fla.	0.566
Del Rio, Tex.	0.300	Port Arthur, Tex.	0.510
Galveston, Tex.	0.498	San Antonio, Tex.	0.362
Hong Kong	0.597	San Fernando, P.I.	0.853
Houston, Tex.	0.450	San Juan, P.R.	0.307
Jacksonville, Fla.	0.464	Savannah, Ga.	0.453
Key West, Fla.	0.357	Tampa, Fla.	0.460
Manila, P.I.	0.560	Thomasville, Ga.	0.440
Miami, Fla.	0.474	Yokohama, Japan	0.408
Mobile, Ala.	0.549		